AN INVESTIGATION OF A CAPACITOR EXCITED INDUCTION GENERATOR EMPLOYING VOLTAGE CONTROL

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Preface

This thesis project was suggested by Dr. J. B. Friauf of the Navy Department, Bureau of Ships. It is a continuation of work done at the U. S. Naval Post Graduate School in 1950 by Lt. C. S. Swift, U. S. N. and at the Massachusetts Institute of Technology in 1952 by R. W. Goode, H. A. Hoffman, and W. F. Searle. Lt. Swift and Goode, Hoffman, and Searle have shown experimentally that the voltage regulation of a capacitor excited induction generator is not acceptable for ordinary use. This project is set up to investigate the possibilities of controlling the voltage of a capacitor excited induction generator, inductively compounded, by use of a saturable reactor in parallel with the shunt exciting capacitor.

The authors wish to acknowledge the assistance given by Dr. J. B. Friauf of the Bureau of Ships and by Professor C. V. O. Terwilliger and Associate Professor C. H. Rothauge of the Postgraduate School and to thank the members of the Electrical Engineering Department of the Postgraduate School for their guidance and assistance.

This work was done between July 1952 and June 1953 at the United States Naval Postgraduate School, Monterey, California.

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r_1	Primary resistance per phase to neutral.
r_2	Secondary resistance per phase to neutral.
X_1	Primary reactance per phase to neutral.
X_2	Secondary reactance per phase to neutral.
X_{cr}	Reactance of shunt exciting branch including capacitor and reactor per phase to neutral.
X_c	Reactance of shunt exciting capacitor alone per phase to neutral.
X_3	Reactance of series inductor per phase to neutral.
r_3	Resistance of series inductor per phase to neutral.
X_r	Reactance of saturable core reactor per phase to neutral.
r_r	Resistance of saturable core reactor per phase to neutral.
X_m	Reactance of magnetizing branch per phase to neutral.
I_m	Current through magnetizing branch. $I_m = I_3$.
I_1	Primary current.
I_2	Secondary current.
s	Slip
ϕ	Phase angle between I_L and E_L.
Y_1	Admittance of the circuit to the right of points A-B, Figure 1-2.
Y_2	Admittance of the circuit to the left of points A-B, Figure 1-2.
Y_m	Admittance of the magnetizing branch of circuit between A and B, Figure 1-2. $Y_m = Y_3$.
W	Watts.
p.f.	Power factor.
E_T	Voltage per phase to neutral across exciting capacitor branch.
E_L	Voltage per phase to neutral across load.

I_L Current thru load per phase to neutral.

I_{cr} Current thru exciting capacitor branch per phase to neutral.

Z Load impedance.

b_m Susceptance of magnetizing branch of Figure 1-2.

i_c Current thru the exciting capacitor per phase to neutral.

i_r Current thru the saturable core reactor per phase to neutral.

I_{dc} Direct current in control winding of saturable core reactor.

E_m Air gap voltage per phase to neutral.

I Direct current to drive motor.

E Voltage applied to drive motor.

$z_1 = r_1 + jx_1$.

$z_2 = r_2 + jx_2$.

$z_3 = r_3 + jx_3$.

$z_r = r_r + jx_r$.

SUMMARY

The purpose of this thesis project was to investigate a scheme for voltage control of a capacitor excited, inductively compounded, induction generator. This involved the use of a fixed capacitor shunted across the generator terminals paralleled with a saturable core reactor to vary the capacitive reactance presented to the machine terminals. The saturable reactor gives rise to harmonics which may appear in the generator stator windings or even in the output voltage signal. This distortion in voltage and current waves was measured.

In addition a method for calculation of generator performance is proposed. This is an extension of the method devised by Dr. J. B. Friauf and enables precalculation of performance when a saturable reactor is used in the voltage control network.

Voltage control was found to be feasible. Load voltage could be maintained constant for all values of load current and load power factor within current and voltage limitations of the induction machine. Calculated performance agreed reasonably well with actual performance. Distortion in the system output voltage wave form was negligible.

Chapter I

SELECTION OF COMPONENTS

Power was developed by a 5 KVA, three phase, 60 cycle, squirrel cage rotor, wye-connected, induction motor used as a generator. The drive was provided by a five horsepower direct current shunt motor. Fixed capacitors were shunted across the terminals of the generator to provide excitation. In parallel with each capacitor was one leg of a three phase saturable reactor controlled by a direct current winding. The reactor provided the means for varying the effective capacitance presented to the machine terminals and, thereby, controlled the generated voltage.

The delta connection for the saturable reactor was chosen because this connection provided a path for the flow of harmonic currents and tended to prevent their appearance in the induction generator windings.

In each line from the shunt exciting branch to the load was placed an air core inductor. These inductors were of such magnitude as to keep the generator generating voltage for all values of load power factor. The output of these series inductors was considered the terminals of the generator system. To these points the load was connected, and the power available at this point was the output of the set.

The 5 KVA, three phase, 60 cycle, induction machine and the five horsepower direct current drive motor were available in the electrical laboratory. This particular induction machine with the

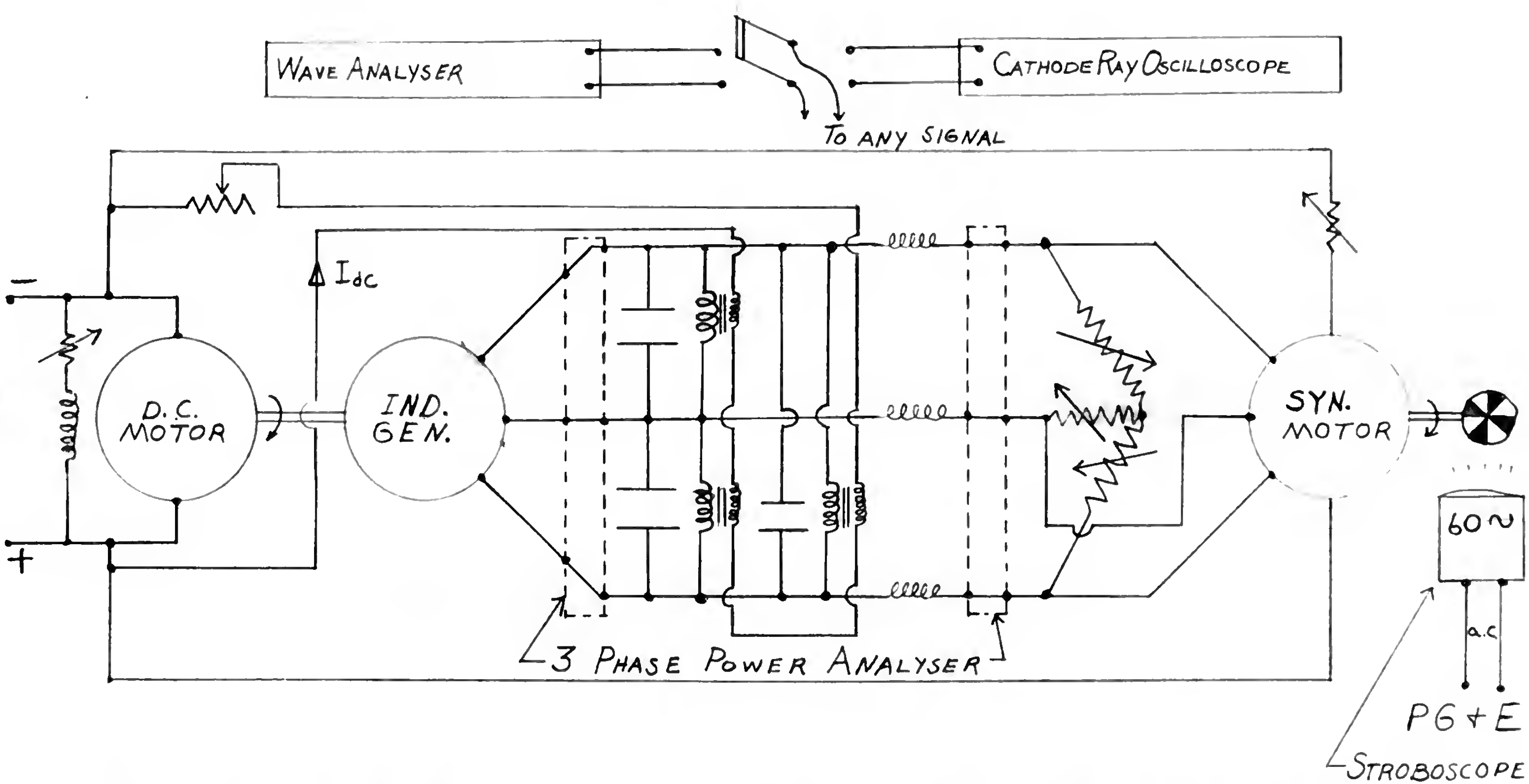
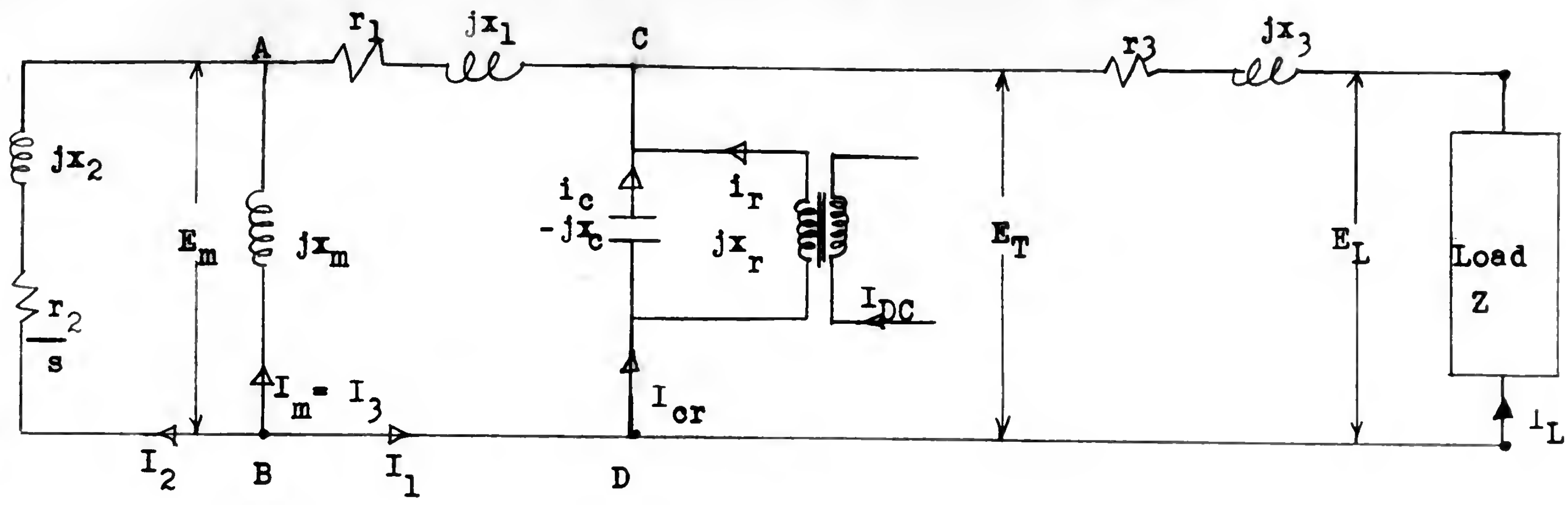


Figure 1-1

Schematic Diagram of Laboratory Set Up For Testing Inductively Compounded, Capacitor Excited, Induction Generator With Voltage Control Arrangement



r_1 = 0.440 ohms.

x_1 = 0.810 ohms.

r_2 = 0.327 ohms.

x_2 = 0.584 ohms.

I_{DC} = 0 to 500 m.a.

x_c = 6.2 ohms.

x_3 = 13.2 ohms.

r_3 = 1.2 ohms.

x_r = variable.

Equivalent circuit for one phase of the inductively compounded, capacitor excited, induction generator.

Figure 1-2

squirrel cage rotor was used because the machine constants were known. They had been determined by Lt. C. S. Swift (7) during his investigation of a capacitor excited induction generator and for our purposes only required verification. Also available was a 5 KVA, three phase, 240 volt saturable core reactor with one direct current control winding controlling all three phases.

With the induction machine and reactor selected more or less by availability, the selection of the remaining components was simple and straight forward.

The value of the shunt exciting capacitance was chosen so that with no control current in the reactor, the generator voltage at no load would not exceed 350 volts, line to line. This particular voltage was selected arbitrarily after consideration of the age and apparent deteriorated state of the stator insulation on the induction machine. A value of 300 volts line to line at the generator terminals was set as a maximum safe voltage for continuous operation. Also entering into the selection of the size of the shunt capacitance was the degree of control desired from the saturable core reactor. It was considered necessary for this investigation to be able, by the use of the saturable core reactor, to control generated voltage from 0 to 350 volts at any load or power factor within the limits of the induction machine. Fortunately the value of capacitance selected for the 350 volt maximum was such that the voltage could be controlled over the entire stipulated operating range by the available reactor. By running the generator with various values of exciting

capacitance and no control current in the reactor, a value of 6.2 ohms was found for X_c which gave a generator voltage of 350 volts, line to line at no load.

With the value of X_c determined and the machine constants known, the value of the series inductance required for the machine to maintain voltage at short circuit was calculated as follows: Under this condition the control current in the saturable core reactor will be zero and X_r will be much greater than X_c. Therefore, X_{cr} will equal X_c approximately. If the generator voltage is to be maintained under short circuit conditions, the short circuit point on the admittance diagram, Figure 1-3, must never fall below the limiting line.

The $-Y_2$ locus may be determined as follows: Friauf, (5)

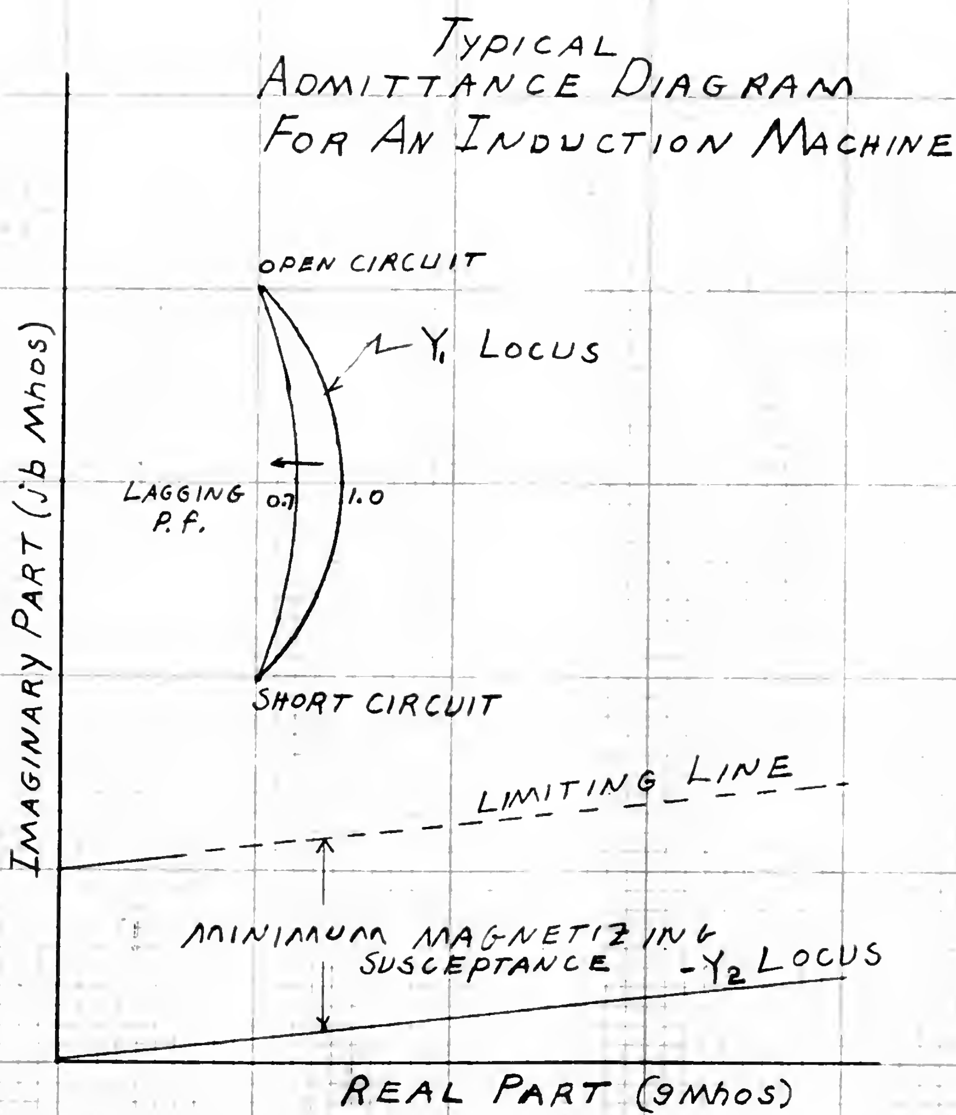
$$\text{radius} = \frac{1}{2X_2} \qquad \text{I-1}$$

$$\text{abscissa of center} = 0 \qquad \text{I-2}$$

$$\text{ordinate of center} = \frac{1}{2X_2} \qquad \text{I-3}$$

The limiting line is determined by drawing a line parallel to the $-Y_2$ locus at a distance above $-Y_2$ equal to the minimum magnetizing susceptance. This value of minimum magnetizing susceptance is obtained from the susceptance curve or magnetizing curve of the induction machine and is discussed in detail in Appendix 2.

It can be shown that the Y_1 locus may be determined as follows: Friauf, (5)



Typical Admittance Diagram For A Capacitor Excited, Inductively Compounded Induction Generator.

Figure 1-3

$$\text{radius} = \frac{\frac{1}{2}X_c\frac{X_c}{X_c-X_3}\sec\phi}{\left(r_1+\frac{1}{2}X_c\frac{X_c}{X_c-X_3}\tan\phi\right)^2+\left(X_1-\frac{1}{2}X_c\frac{X_c-2X_3}{X_c-X_3}\right)^2-\left(\frac{1}{2}X_c\frac{X_c\sec\phi}{X_c-X_3}\right)^2} \qquad \text{I-4}$$

The center of the circle is the point having an abscissa of:

$$\frac{r_1+\frac{1}{2}X_c\frac{X_c}{X_c-X_3}\tan\phi}{\text{Same Denominator as I-4}} \qquad \text{I-5}$$

and an ordinate of:

$$\frac{-X_1+\frac{1}{2}X_c\frac{X_c-2X_3}{X_c-X_3}}{\text{Same Denominator as I-4}} \qquad \text{I-6}$$

Such a locus for Y_1 is shown in Figure 1-3. As the load power factor is varied a family of circles is found for the locii of Y_1. The centers of these circles move to the left as the load power factor becomes more lagging. However, all circles pass thru the same open circuit and short circuit points. The minimum value of X_{cr} determines the open circuit point while the short circuit point is determined by the value of X_3. As X_3 increases the short circuit point moves up and as X_3 decreases the short circuit point moves down. The problem is to choose the minimum value of X_3 which will keep the short circuit point above the limiting line on Figure 1-3.

By trial and error methods employing equations I-1 to I-6 and by using Figure 1-3, the optimum value of X_3 was found to be 8.5 ohms inductive reactance for each line. An air core coil of this particular rating with the desired current carrying capacity was not available in the electrical laboratory. However, six air core coils of 13.2 ohms inductive reactance each were available and were used to make X_3 13.2 ohms or in parallel to make X_3 6.6 ohms. It was considered that an investigation with each of the above two values for X_3, while not the optimum value, would serve the purpose of this study and show the effects of over and under compounding.

The load selected was a 5 KVA synchronous motor, 220 volt, with a synchronous speed of 1200 RPM at 60 cycles, with a parallel wye connected bank of variable resistors. This arrangement afforded a wide range of loads at any desired power factor. A synchronous motor load was almost a necessity because it supplied an excellent means for measuring generator slip and at the same time afforded a means for controlling load power factor.

Chapter II

EXPERIMENTAL PROCEDURE

The performance of this particular induction generator and voltage control arrangement was tested at various loads and at various power factors both leading and lagging. Load power factors less than 0.6 lagging are seldom encountered in small distribution systems in shipboard applications for which this arrangement seems best suited. Values of X_3 above and below the optimum value were tried. The significant data which was taken is listed or discussed below:

Generator current, I_1, generator voltage, E_T, and the power developed by the generator were measured with a Weston, Type 2, Model 639, three phase, industrial analyser.

Reactor control current, I_{dc}, alternating coil current of the reactor, i_r, and net exciting branch current, I_{cr}, were measured with appropriate ammeters.

Load current, I_L, load voltage, E_L, load power, and load power factor were measured with a Westinghouse, Type TA, three phase, industrial analyser. The load was a three phase synchronous motor in parallel with a wye connected resistor bank. Negligible distortion in the output voltage wave form was introduced by the load. Some slot harmonics were present in the wave form of E_L, but these were of a high order and very small. The synchronous motor gave good power factor control and the three phase wye connected load

was in balance to within plus or minus five percent.

Slip measurement was necessarily precise. Close speed control was provided by varying the shunt field rheostat of the direct current drive motor. A target was mounted on the end of the synchronous motor shaft at which was aimed a stroboscope tuned to the frequency of the Pacific Gas and Electric Company's power supply (60 cycles per second). The generator drive motor speed was adjusted until the target appeared to stop, at which time the generator speed was measured with a chronometer type tachometer. Since the synchronous speed of the induction generator at 60 cycles per second was the same as that of the synchronous motor load, namely 1200 RPM, slip RPM was determined by subtracting 1200 from the tachometer reading.

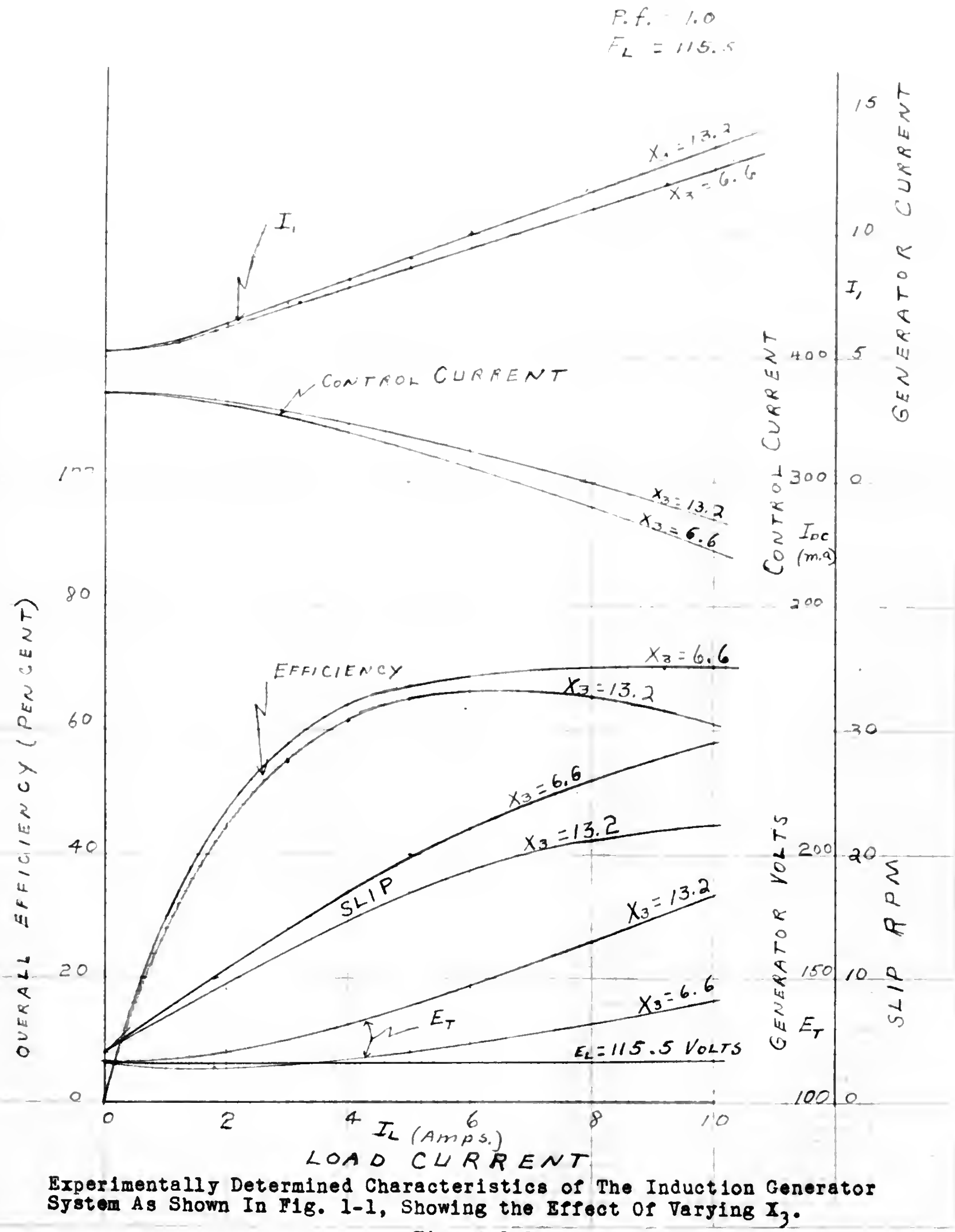
The analysis of the output voltage wave, E_T, and the generator current wave, I_1, was determined with a General Radio, Type 736-A, wave analyser. Cathode-Ray oscillograph pictures of the wave forms were recorded by use of a Polaroid Land Camera adapted to this particular use. Typical wave form pictures are shown in Figure 3-5.

Chapter III

The results of the various runs are shown as curves in Figures 3-1 to 3-4. Figures 3-1 and 3-2 compare generator performance resulting from two different values of X_3. Figures 3-3 and 3-4 show how generator performance is effected by various load power factors. All experimental data is tabulated in Appendix 5. The load voltage, E_L, was maintained constant during all experimental runs.

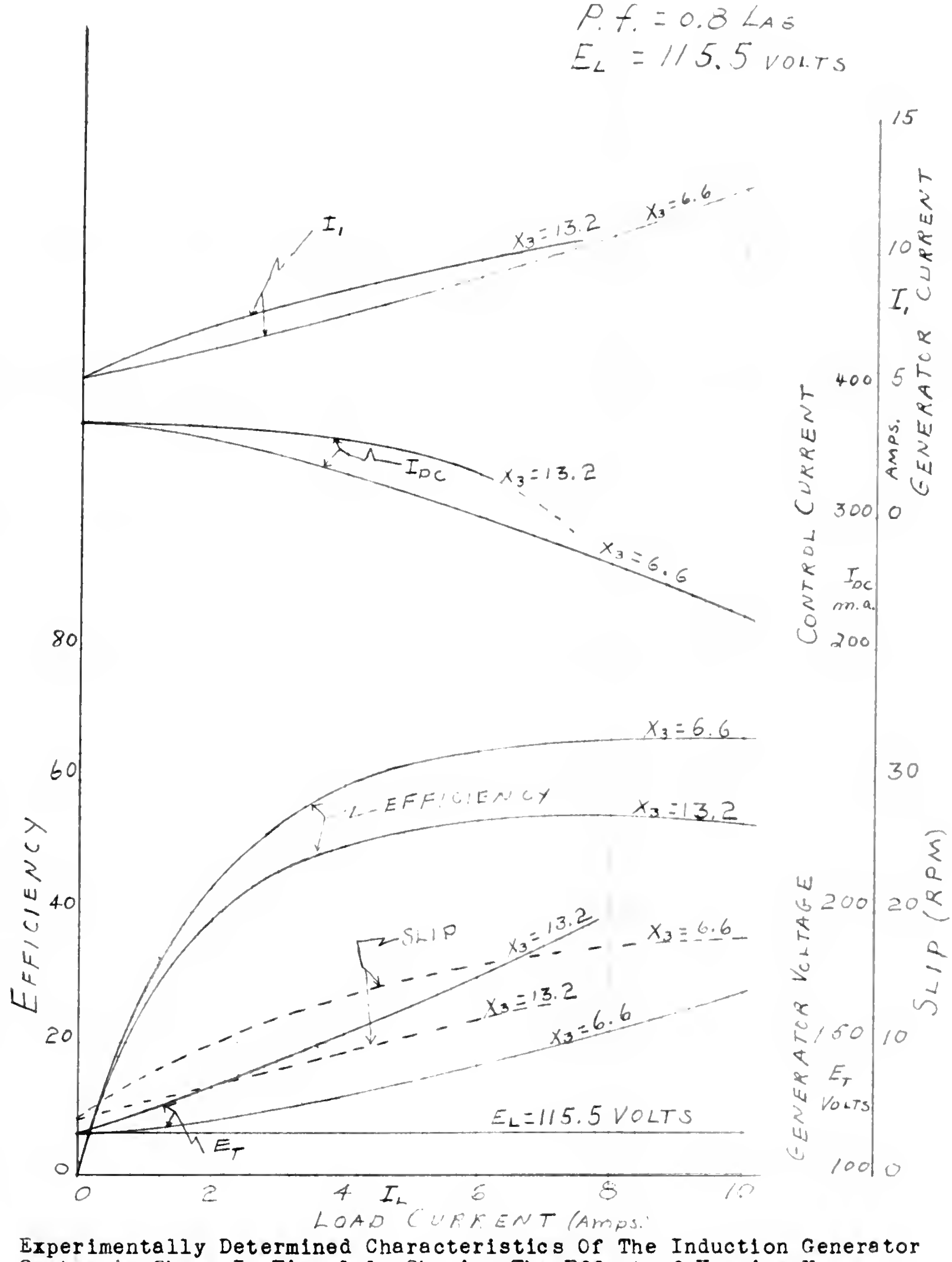
As shown by Figures 3-1 and 3-2, I_1 increased slightly when higher inductive compounding was used. I_{dc} is best compared on the basis of no load to full load current change required. For unity power factor load this change was about 165 milliamperes. For 0.8 lagging power factor the total change in I_{dc} was 175 milliamperes. These values of I_{dc} as determined by the load current and load power factor would be of interest in adapting this circuit to automatic voltage control. Depending upon the constants of the saturable reactor, a considerable time delay could occur in establishing a required change in I_{dc}. This would limit the speed of response of an automatic voltage regulator. Cockrell, (4).

Efficiency decreased as series inductance increased and as power factor of load decreased. The best efficiency obtained was seventy percent and this at unity power factor load with the generator system under compounded. Efficiency was computed as the ratio of the output power at the set terminals to the power input to the generator drive shaft.



Experimentally Determined Characteristics of The Induction Generator System As Shown In Fig. 1-1, Showing the Effect Of Varying X_3.

Figure 3-1



Experimentally Determined Characteristics Of The Induction Generator System As Shown In Fig. 1-1, Showing The Effect of Varying X_3. Load Power Factor Equal to 0.8 Lag.

Figure 3-2

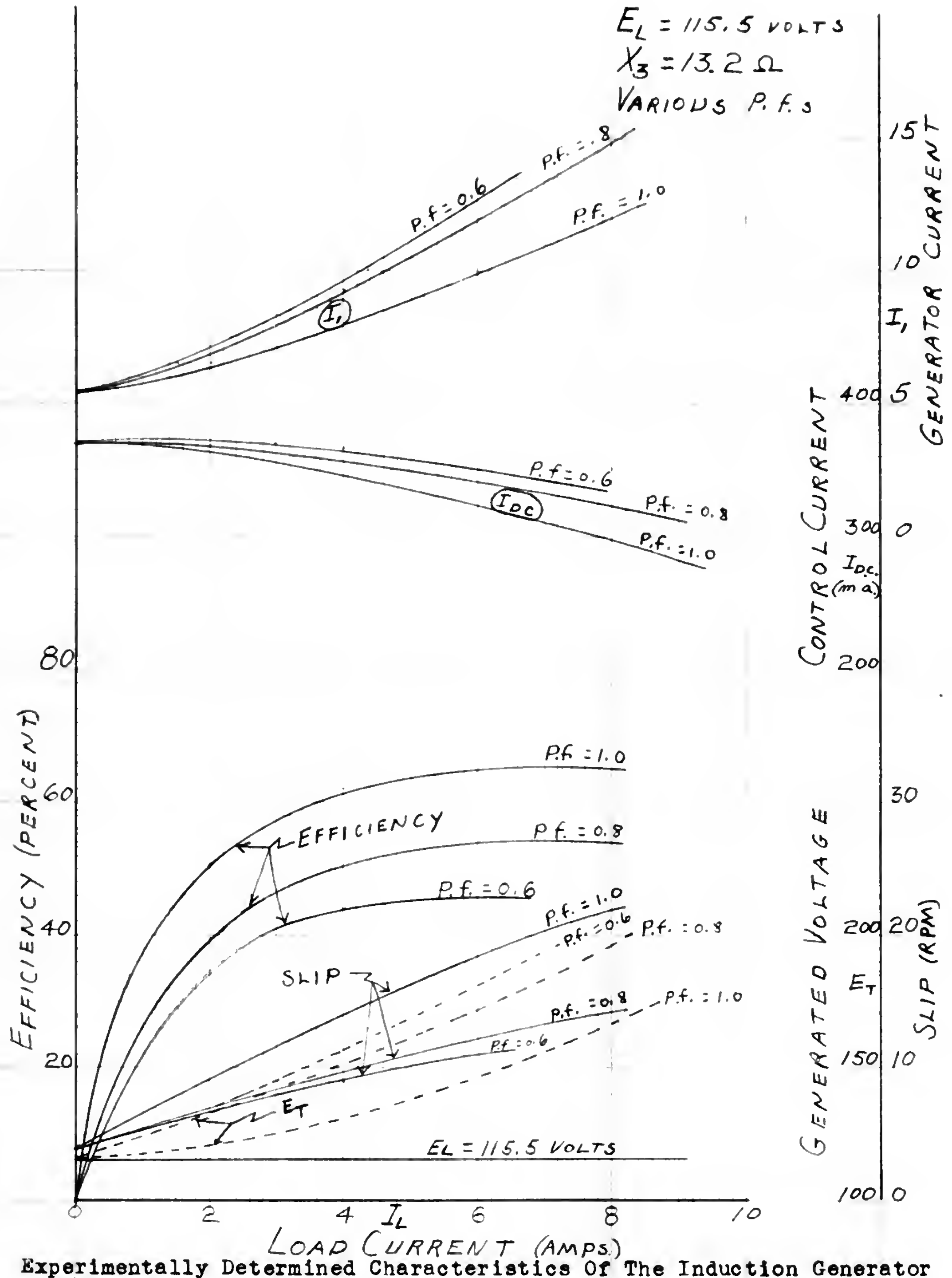
Slip decreased for a fixed load current and voltage as X_3 increased. This is consistent with the behavior predicted from the circle diagram. As X_3 increases E_T increases for a fixed E_L and I_L. These slip curves would be used in the design of an automatic device for maintaining a constant frequency output. Maximum slip was about thirty revolutions per minute.

Figures 3-3 and 3-4 show the effect of load power factor on machine performance for fixed values of series inductance, X_3. Efficiency fell off as load power factor angle increased. The span of load power factor, unity to 0.6 lagging, represents the operating range encountered in generating systems aboard ship.

The wave forms of chief interest are those of E_L and I_1. A good wave form of output voltage is required for proper operation of induction motors. A badly distorted wave form of generator current could lead to parasitic torques which would tend to reduce the efficiency of the generator. This is especially true if a fifth harmonic of field flux is present. Alger (1).

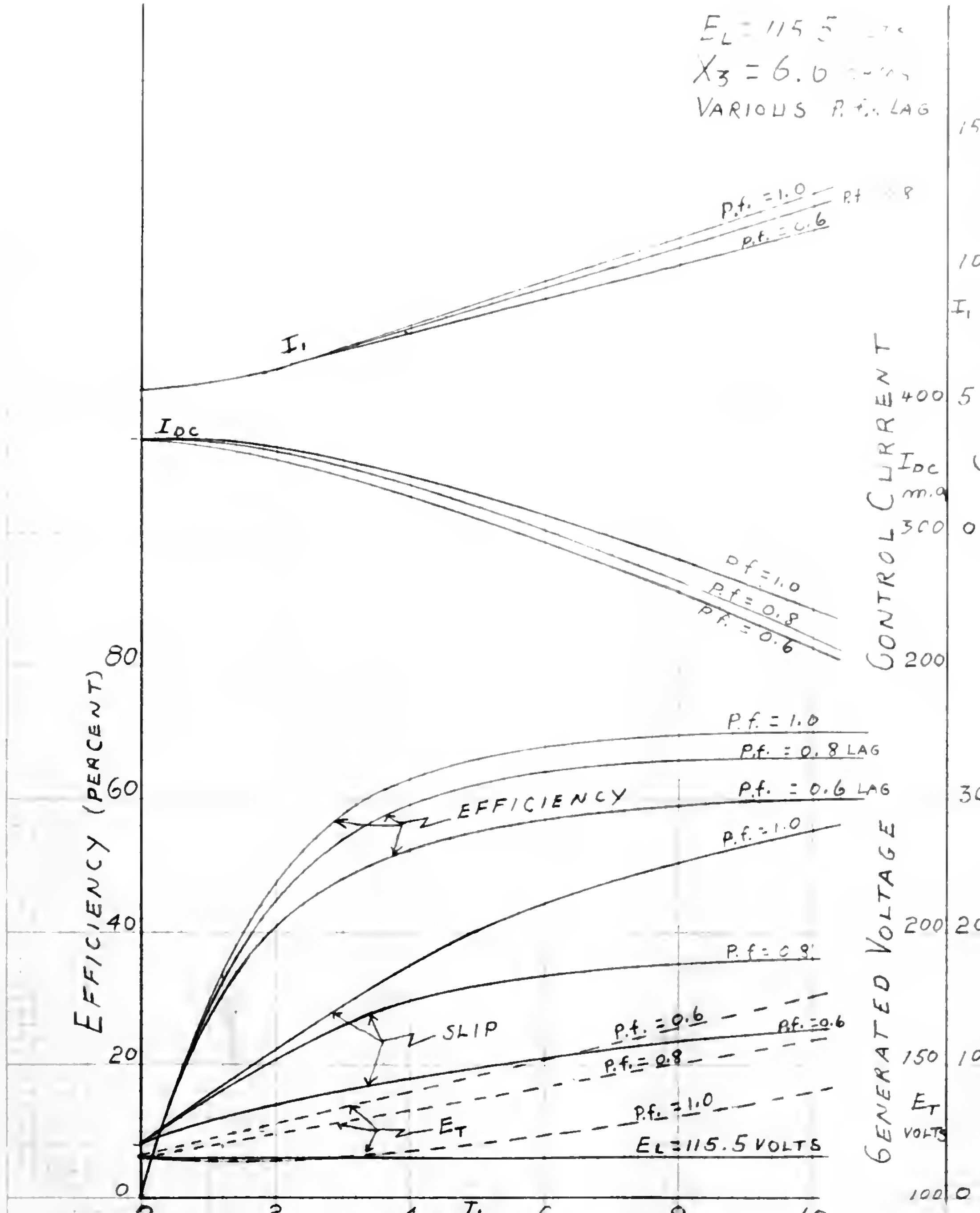
The worst distortion in I_1 and E_L occurred at high saturable reactor alternating current which corresponds to small load current. Third harmonics appeared but these were small and were probably due to a slight unbalance at the load.

With X_3 equal to 13.2 ohms the fifth harmonic component of E_L under the worst conditions of loading reached a value of one percent of the fundamental. With X_3 equal to 6.6 ohms the fifth harmonic component of E_L reached 2.8 percent of the fundamental. Seventh harmonic



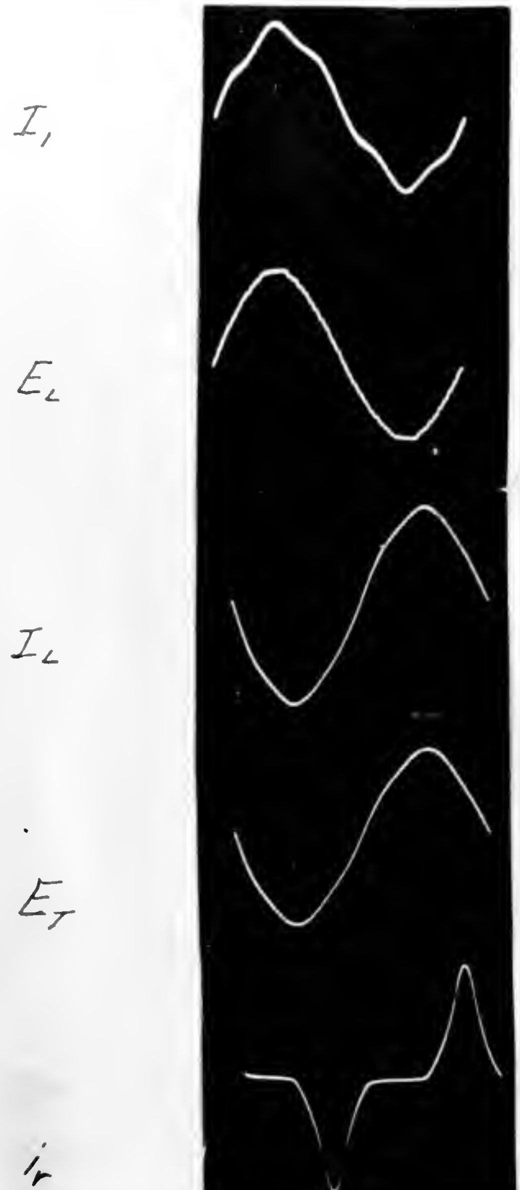
Experimentally Determined Characteristics Of The Induction Generator System Shown In Fig. 1-1, With X_3 Equal To 13.2 Ohms, Showing Effect Of Varying Load Power Factor

Figure 3-3



Experimentally Determined Characteristics Of The Induction Generator Shown In Fig. 1-1, With X_3 Equal to 6.6 Ohms, Showing Effect Of Varying Load Power Factor

Figure 3-4



Experimentally Determined Curves Showing Current and Voltage Wave Forms In The Induction Generator System Shown In Fig. 1-1, X_3 Equal to 13.2 Ohms and Load Power Factor Equal to o.8 Lagging.

Figure 3-5

components in each of the above cases did not exceed 0.4 percent of the fundamental.

With X_3 equal to 13.2 ohms the fifth harmonic component in I_1 under the worst conditions of loading reached 8.2 percent of the fundamental. With X_3 equal to 6.6 ohms this component was 6.4 percent of the fundamental. Seventh harmonics of 1.4 percent were observed in I_1 with X_3 equal to 13.2 ohms.

The current harmonics flowing in the saturable reactor were high. At the worst condition with 290 volts impressed across each reactor coil, 12.5 amperes flowing in each coil, and I_{dc} equal to 400 milliamperes, the following harmonic values were obtained:

Order of Harmonic	Magnitude in Percent of Fundamental
3	66
5	32
7	16
9	10
15	2

No appreciable even order harmonics were detected. For a constant control current, the distortion in the reactor coil current wave form decreased with a decrease in applied alternating voltage. For example, with coil voltage equal to 200 volts, I_{dc} equal to 400 milliamperes, and reactor coil current of 9 amperes, the reactor coil current, i_r, wave analysis was:

Order of Harmonic	Magnitude in Percent of Fundamental
3	51
5	16
7	4.8
9	3.6

This distortion depends upon the degree to which the reactor saturates as the alternating voltage is increased. Figure 4-2 shows that with no direct current flowing, this reactor does not saturate until the applied voltage across each leg reaches about 300 volts. The delta connection for the reactor coils, which provides a path for circulating currents, is helpful in preventing excessive distortion in I_1 and E_L wave forms. Distortion in I_1 and E_L should very definitely be considered in the choice of a saturable reactor for such an application as this. Boyajian (3).

The wave form of E_L appears to have been improved by the filtering action due to the series inductance and shunt capacitors. With X_3 equal to 13.2 ohms the analysis of E_L showed only one percent fifth harmonic. The capacitor-series inductor configuration is that of a low pass filter. For this filter arrangement cut off frequency begins when X_3 is equal to X_{cr}. Above this frequency attenuation begins. For an X_3 of 13.2 ohms and an X_{cr} of 6.2 ohms the cut off frequency is about 71 cycles per second. For an X_3 of 6.6 ohms and an X_{cr} of 6.3 ohms the cut off frequency is 102 cycles per second.

The saturable reactor and series inductors involved in this circuit acted to limit the output and reduce the set efficiency. As an

example of the attenuation taking place, using an X_3 of 13.2 ohms, a volt ampere output of 3450 was obtained for the set at full load current and unity power factor load. The corresponding volt ampere output delivered by the generator was 7480. Under the same conditions but using an X_3 of 6.6 ohms, the volt ampere output for the set was again 3450, but the generator volt ampere output was 5250. The highest efficiency was seventy percent. At 0.6 lagging power factor the attenuation was much worse:

X_3	Volt Ampere Generator Output	Volt Ampere System Output	Efficiency
13.2	7680	2280	46%
6.6	6850	3520	60%

Efficiency might be improved with an induction machine designed as a generator with low magnetizing current required and higher values of X_c permissible.

A three phase short circuit was applied to the output terminals. With an X_3 of 13.2 ohms the short circuit current was sustained at 13 amperes. E_T was easily controlled and I_1 was 9.7 amperes. With an X_3 of 6.6 ohms, or under compounding, the generator did not maintain voltage under short circuit load.

The machine had a measure of self-protection due to the series inductor which limited the short circuit current depending upon the value of E_T developed. At the same time the generator current was not excessive.

An induction motor of 5 KVA rating was successfully started several times by this generator system, motor under no load. A 5 KVA, 220 volt synchronous motor was started under no load many times with this set. No other loading tests were made, but these results were considered good and were chiefly due to the voltage control feature resulting from the saturable reactor. The induction motor and synchronous motor were started under no load; however, it must be remembered that they were of the same rating as the induction generator itself.

Loads having power factors as low as 0.2 lagging were applied to the terminals of this set. Voltage could be easily controlled under these conditions although the current supplied to the load was small because of the upper voltage limit stipulated for the generator itself. A practical design of an induction generator should, for this reason, permit a relatively high voltage limit for continuous operation.

After the induction generator system had been in operation for some time and had reached normal operating temperatures, and in some case exceeded normal temperatures, it became impossible to control the generator voltage in the vicinity of 300 volts by varying the reactor control current. In other words, the generator voltage rose to the maximum value, 350 volts, line to line, and stayed there. It was not possible to bring it down by use of the reactor. Under these conditions the exciting capacitors were switched out of the circuit momentarily and then reinserted. The voltage was then brought up slowly by reducing I_{dc}, with special care being taken not to exceed 300 volts.

It is evident from the above situation that the control reactor in this case was operating near or above the maximum point of control. Also the ability of the reactor to control the voltage decreased with an increase in reactor coil temperature. Under this condition of operation when an attempt was made to reduce the generated voltage by increasing the reactor control current, X_r was reduced to a minimum value. With X_r small, $(r_r + jX_r)$ is appreciably affected by the value of r_r. Therefore, as r_r increased with a temperature increase, z_r increased appreciably. This in turn caused a decrease in X_{cr} and an increase in E_T. Also, in this region of operation with E_T about 300 volts, line to line, and I_{dc} at the maximum value of 0.5 amperes, it is shown by the reactor characteristics in Figure 4-2 that X_r increases appreciably with an increase of E_T. Therefore, these two related effects, increase in r_r with a temperature rise and an increase in X_r with a rise in E_T, worked together as a chain reaction causing E_T to increase to 350 volts, line to line. The system in this condition was such that the reactor had no control of the generated voltage.

In the practical design of such a system as this, the point of loosing control of the voltage would need thorough investigation. Although a reactor of as low rating as possible is desirable from the point of view of efficiency, the reactor must be large enough in rating to control the voltage under every possible circumstance. This would mean that the reactor rating would necessarily be large to include a

suitable factor of safety.

As shown by Figure 3-4, only a very small change in I_{dc} was required when I_L changed from 0 to 2 amperes. A much greater change in I_{dc} was required when I_L changed from 8 to 10 amperes. In other words, when the load current was small, a very small change in I_{dc} caused a large change in E_T. When the load current was large a large change in I_{dc} was required to make an appreciable change in E_T. Since I_{dc} was controlled manually, this system was more stable or easier to control at high loads than at low loads. At low loads even a slight fluctuation of the DC supply voltage was sufficient to cause the induction generator voltage to vary considerably. Therefore, the manual controller was constantly changing I_{dc} up and down to maintain a constant load voltage.

Chapter IV

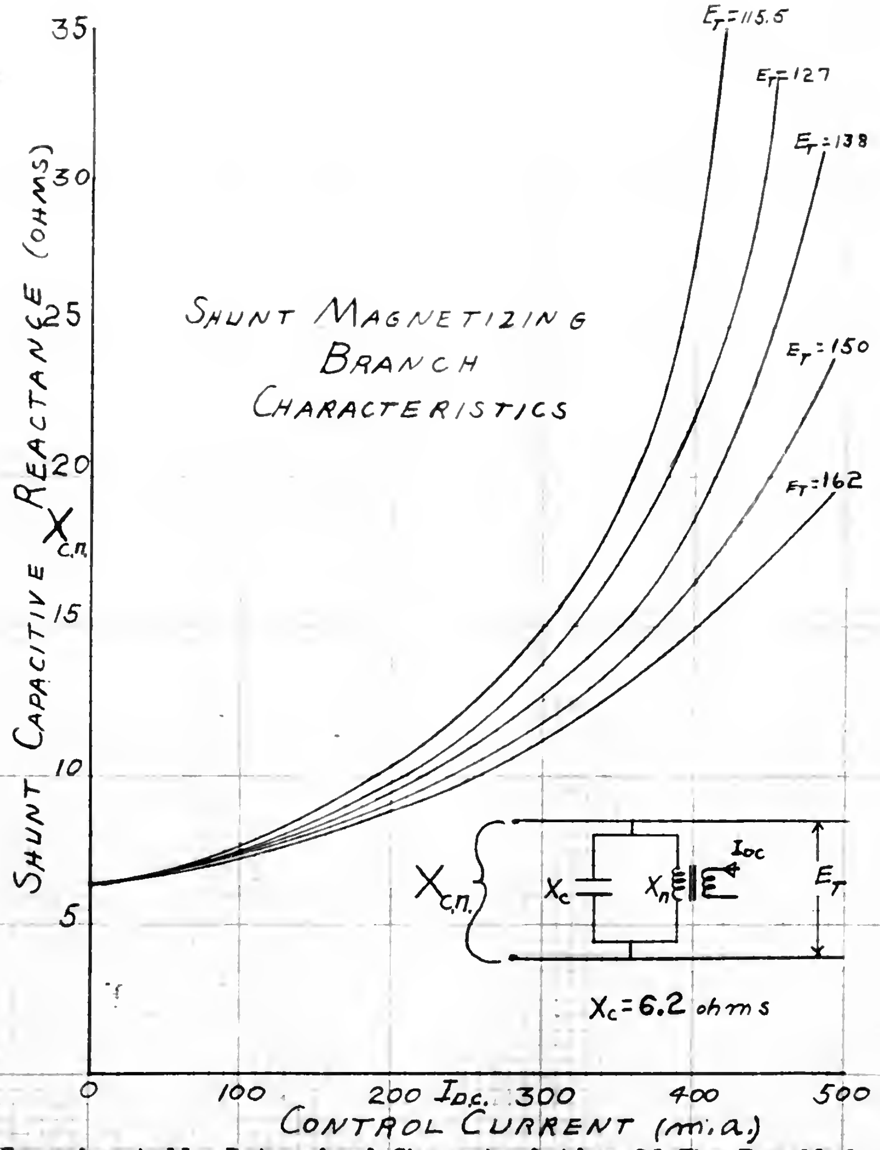
PERFORMANCE CALCULATION

Dr. James B. Friauf's method for performance calculation using a constant exciting capacitor is shown in detail in Appendix 3. In order to take into consideration a variable exciting capacitance which results from maintaining the load voltage constant, it was necessary to extend Dr. Friauf's method as described below.

A set of characteristic curves were made up for the saturable core reactor and parallel capacitor combination as is shown in Figure 4-1. These curves are peculiar to this particular reactor. They may be considered similar to the characteristic curves of a vacuum tube. The reactor is a non linear device and as such does not lend itself readily to computation. No design data was available on the saturable core reactor. However, by the use of curves shown in Figure 4-1, the capacitative reactance of the parallel shunt branch can be predicted if we know the control current and the alternating voltage applied to the terminals, E_T. Or, if we know E_T and a required X_{cr}, we may find a corresponding I_{dc}.

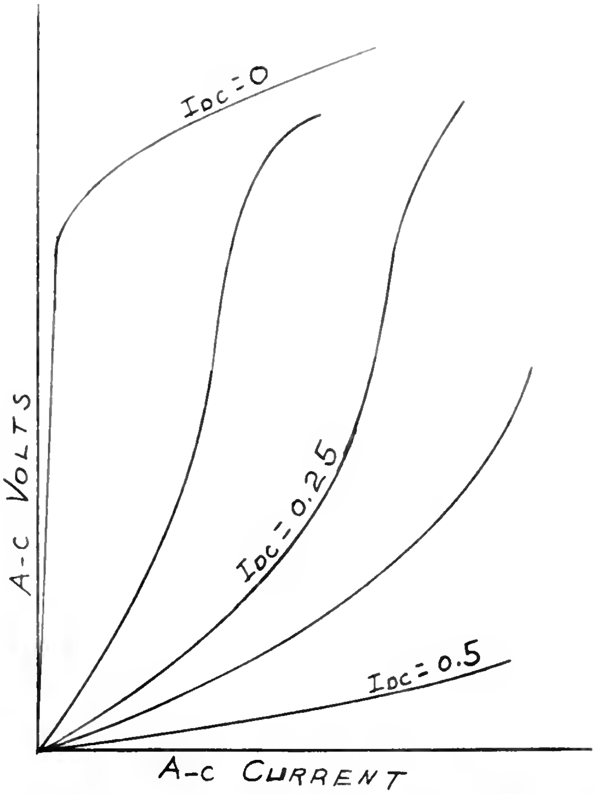
If we were making a theoretical design for this system and had selected a generator, a fixed value for X_c, and a saturable core reactor, curves such as shown in Figure 4-1 could be prepared by use of information such as shown in Figure 4-2. This information should be available with any reactor design.

By the method of Dr. Friauf, assuming particular values for X_{cr}, a series of curves was computed for unity power factor loads and



Experimentally Determined Characteristics Of The Parallel Arrangement Of The Shunt Magnetizing Branch Of The Induction Generator System Shown In Fig. 1-1.

Figure 4-1



Typical Characteristics Of A 220 volt, 5 KVA, Saturable Core Reactor.

Figure 4-2

plotted as shown in Figure 4-3. Details of these computations are shown in Appendix 3. We note that if we draw a line corresponding to a constant load voltage of 115.5 phase volts to neutral on Figure 4-3, we may then pick off enough information to make a plot of X_{cr} required for various values of load current. This curve is shown as Figure 4-4a.

Now calculate and make a plot of E_T versus I_L for unity power factor loads with X_3 equal to 13.2 ohms and E_L equal to 115.5 volts. This curve is shown in Figure 4-5b. Now, we note that we have computed values for E_T and X_{cr} corresponding to a particular load current, voltage and power factor. We may enter curves in Figure 4-1 with these computed values of E_T and X_{cr} and determine the value of I_{dc} required.

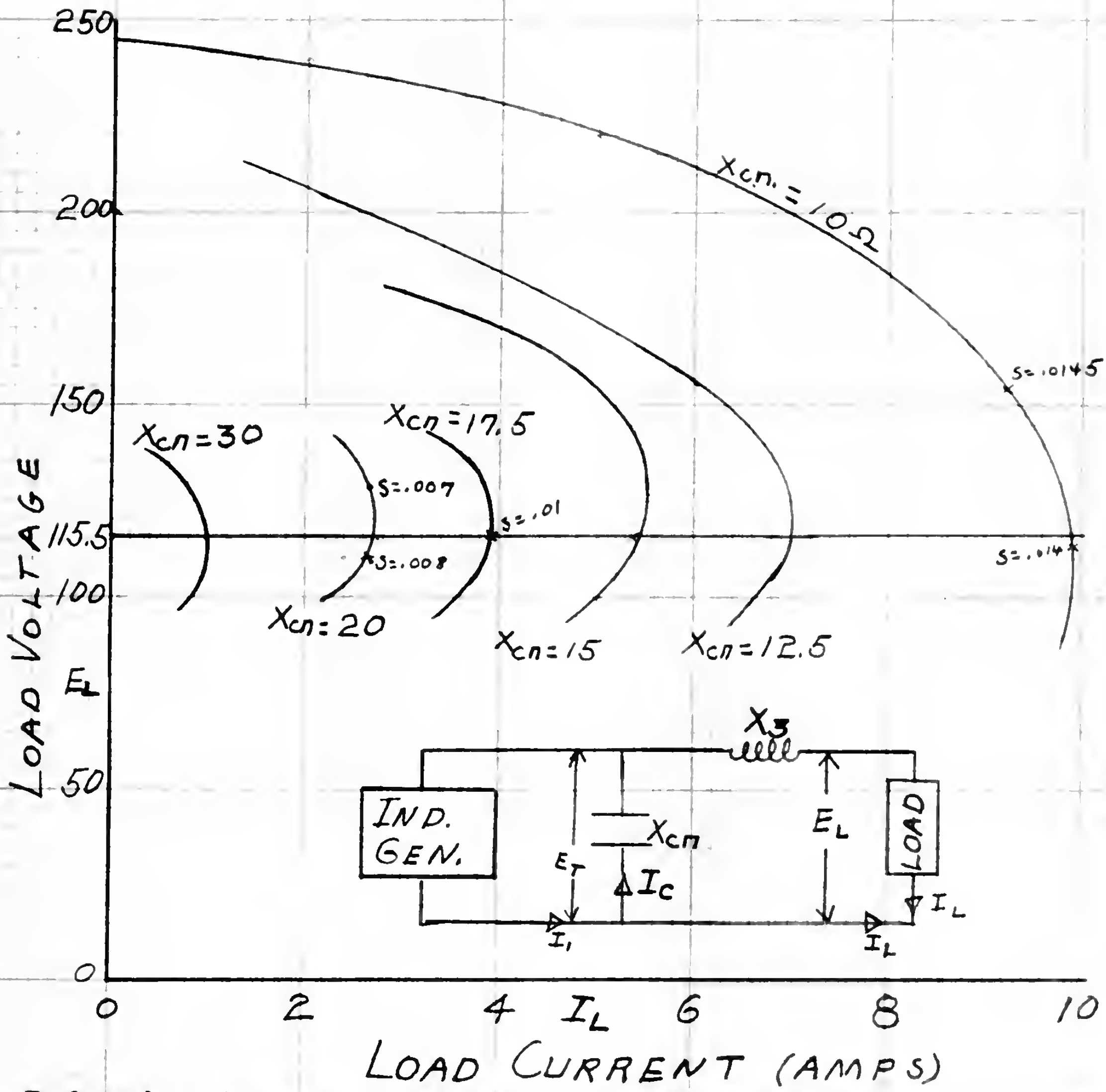
To summarize the procedure for predicting what happens in the equivalent circuit under various load currents, at a certain load voltage (E_L-115.5 volts), and a certain load power factor (unity), proceed as follows:

1. Select a value for I_L.
2. Enter curve in Figure 4-5b with chosen I_L and pick off a corresponding E_T.
3. With I_L enter curve in Figure 4-4a and pick off required X_{cr}.
4. With X_{cr} and E_T enter curve in Figure 4-1 and select I_{dc}.
5. By a slight amount of interpolation with

CALCULATED EXTERNAL CHARACTERISTICS

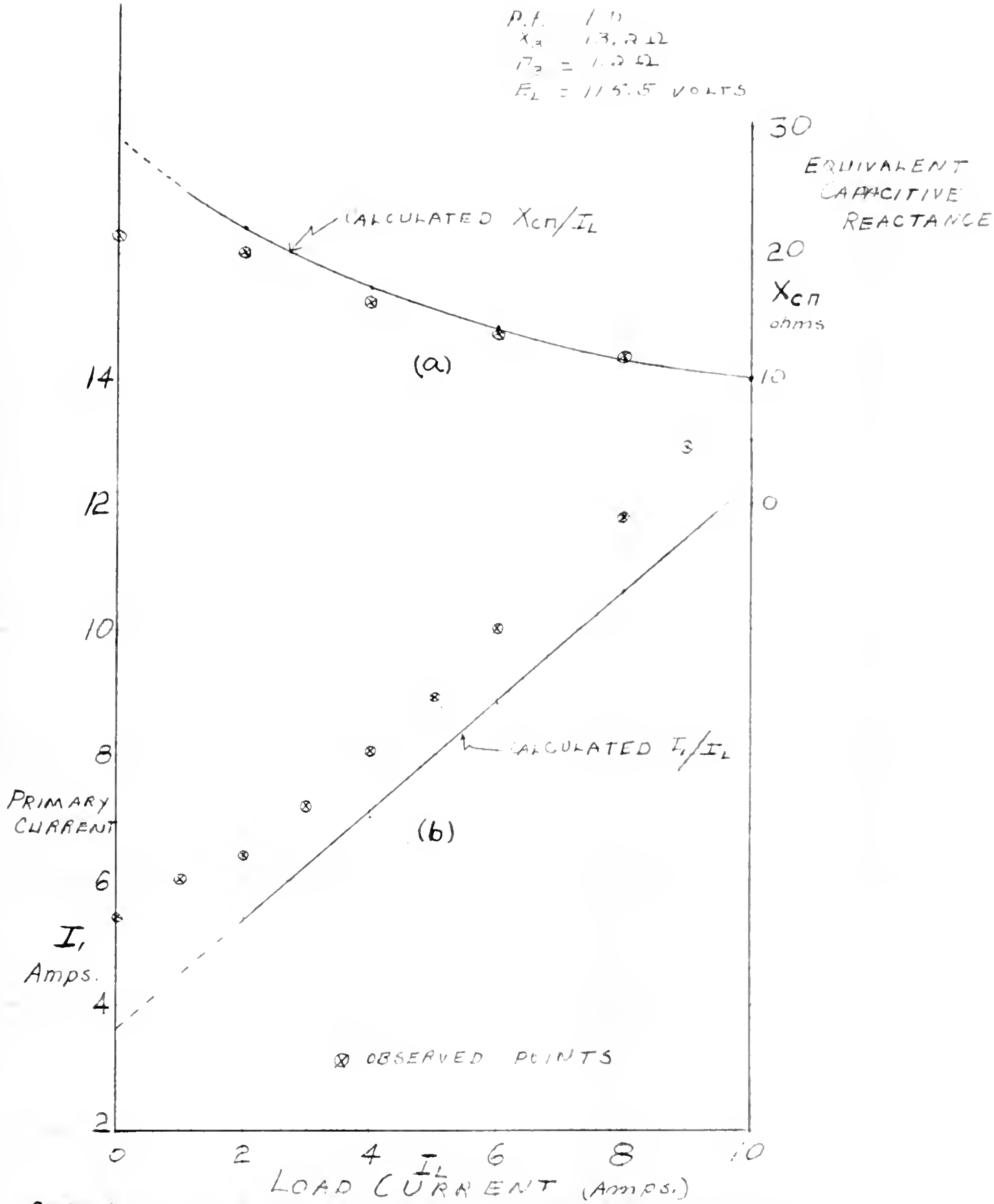
LOAD P.f. = 1.0

$X_3 = 13.2$



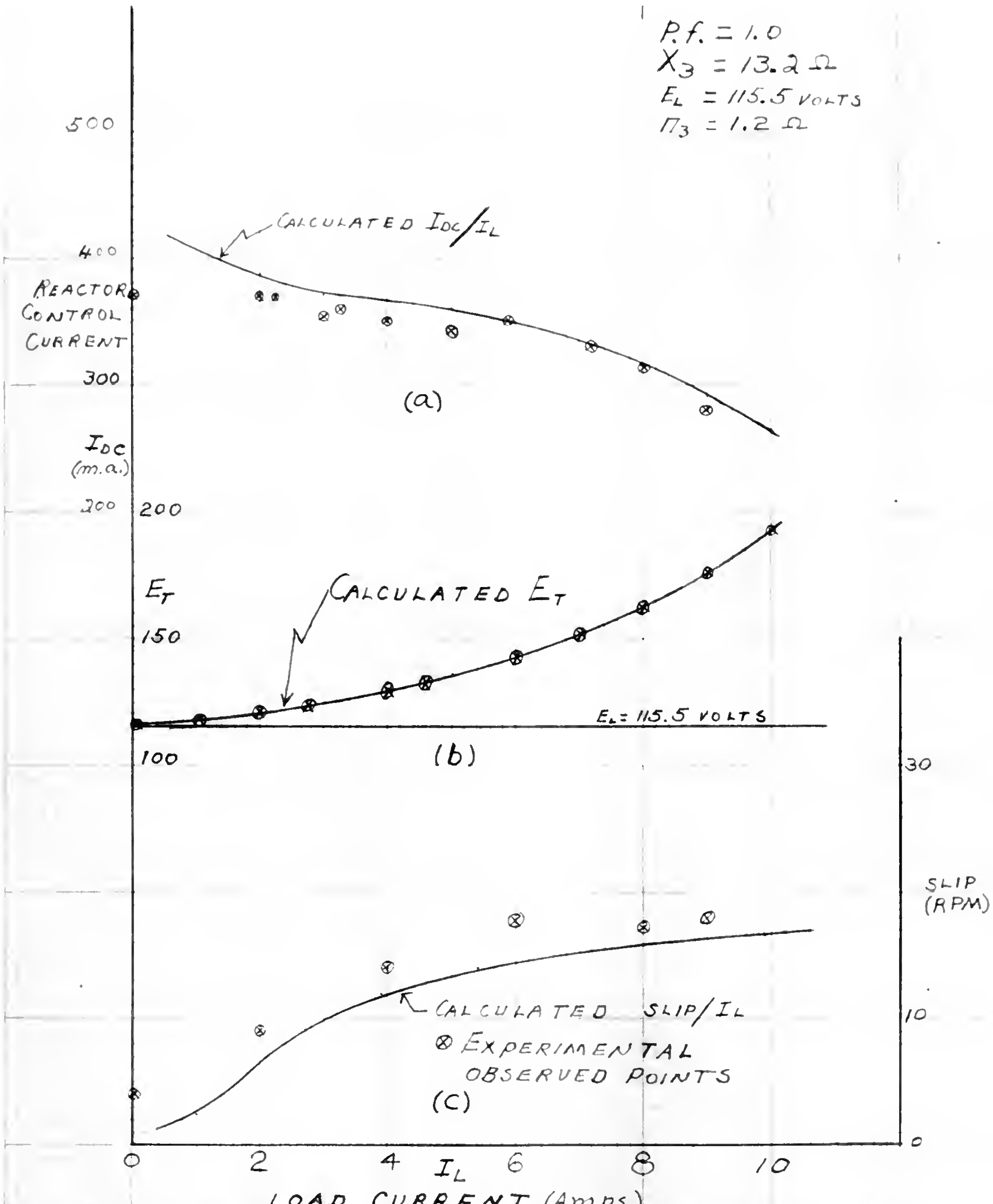
Induction Generator External Characteristics Calculated For Various Values Of Exciting Capacitive Reactance, X_{cr}, And For Fixed Series Inductance and Fixed Load Power Factor.

Figure 4-3



Comparison Of Calculated And Experimentally Determined Values Of I_1 and X_{cr} For Induction Generator System Shown In Fig. 1-1.

Figure 4-4



Comparison Of Calculated And Experimentally Determined Values Of I_{dc}, E_T', and Slip For The Induction Generator System Shown In Fig. 1-1

Figure 4-5

the computed data for Figure 4-3, values of generator slip and generator current for this chosen value of I_L can be determined. For example consider in Figure 4-3 the curve for X_{cr} equals 10 ohms, $E_L = 115.5$ volts, $I_L = 9.9$ amperes. The estimated slip is between .014 and 0.0145 and nearer 0.014. To compute I_1 corresponding to a particular I_L and E_L proceed as follows:

$$\bar{E}_T = \bar{E}_L + \overline{I_L Z_3} \qquad \text{IV-1}$$

Enter curve in Figure 4-4a with I_L and pick off X_{cr}.

$$\bar{I}_{cr} = \frac{\bar{E}_T}{\bar{X}_{cr}} \qquad \text{IV-2}$$

$$\bar{I}_1 = \bar{I}_L + \bar{I}_{cr} \qquad \text{IV-3}$$

Figures 4-4 and 4-5 show a series of curves calculated by the above method for unity power factor load with a series inductance, X_3, of 13.2 ohms and a constant load voltage, E_L, of 115.5 volts. Along with the calculated curves are shown points which have been determined by actually running the machine under the specified conditions.

In Figure 4-5c the calculated slip curve agrees very well with the experimental points. The slight deviation between calculated values and experimental values could be the result of inaccuracies in slip measurement or possibly the interpolation for slip in Figure 4-3.

As shown in Figure 4-5b the calculated values for E_T agree with the experimental values. This simply means that X_3 was accurately determined. This curve is shown only to give a complete picture of what is happening in the generator network.

Also in Figure 4-5a the calculated values for I_{dc} agree reasonably well with the experimental values, the larger deviations existing at low values of load current.

Figure 4-4b shows a considerable discrepancy between calculated and observed values of generator current, I_1. This may be the result of a simplifying assumption made in Dr. Friauf's method of calculation. One assumption is that it is sufficient to consider only the fundamental of generator current. This investigation showed that under low load conditions (corresponding to high alternating current in the saturable reactor) a fifth harmonic current nearly ten percent as great as the fundamental existed in the generator stator windings. This may account for about half of the discrepancy. On the other hand it must be remembered that the calculated value for I_1 was at best a rough estimate, the accuracy depending upon a multitude of factors. The fact that the measured and calculated values for I_1 show the same general trend indicates that this method of calculation has some merit.

It is seen in Figure 4-4a that the calculated values for X_{cr} agree to a certain extent with the experimental points.

Chapter V

CONCLUSIONS

The authors feel that the objectives of this investigation have been attained. It has been shown that it is possible to predict the performance of this inductively compounded, variable capacitor excited, induction generator to a reasonable degree of accuracy. It has been demonstrated that the output voltage of this generator network can be kept constant for all loads within the current and voltage limits of the machine. With the proper choice of the series inductance, the generator will continue to generate voltage and the current will be kept within safe limits even under short circuit conditions at the load.

Although current harmonics of considerable magnitude appear in the control network, they appear to a much smaller degree in the generator windings. The output voltage at the load terminals of this system is practically a pure sine wave.

The overall efficiency of this generating system is lower than that of a standard alternator of equal rating. However, because of speed limitations on a standard alternator and apparently no speed limitations on a squirrel cage rotor induction machine of this type, it is believed that a system of this general nature may possibly prove desirable at high frequencies and low power ratings. The authors do not feel that a system such as this would be feasible for large power ratings. Since efficiency is such an important factor in large power generating systems, it is felt that the induction generator system as here described would probably never favorably compete with present day

large alternators. Also, the size and cost of the exciting capacitors, saturable reactors and series inductors would certainly be decided disadvantages of the capacitor excited induction generator in large ratings.

Chapter VI

RECOMMENDATIONS

It is recommended that further study be made of this system of voltage generation with regard to automatic voltage control. Since load voltage may be kept constant for all loads and load power factors simply by varying the reactor control current over a range of zero to about 0.4 amperes, it should be an easy matter to design a suitable electronic device to perform this task. Furthermore, in view of the probable use of higher frequencies in naval applications, it is suggested that any future investigations along this line be made at 400 cycles per second or greater. Higher frequencies would probably lead to smaller components and possibly a higher overall efficiency.

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APPENDIX 1

Induction Machine Constants

The induction machine constants used in this experiment were those determined by Lt. C. S. Swift in his investigation with this same machine and are as follows:

r_1 - 0.440 ohms

X_1 - 0.810 ohms

r_2 - 0.327 ohms

X_2 - 0.584 ohms

These constants were roughly verified by making a blocked rotor test, a voltmeter-ammeter-wattmeter test on two stator phasesin series, and a DC bridge measurement of r_1. In view of the excellent procedure used by Lt. Swift in his determination of these constants and of the good results he obtained when using them in performance calculations, it was not considered justifiable to devote additional time and effort to their very accurate determination or precise verification.

APPENDIX 2

Magnetization or Susceptance Curve

The Susceptance curve was determined as follows:

a - The induction machine was driven at synchronous speed by the direct current drive motor.

b - Sixty cycle voltage was applied to the machine terminals.

c - Applied voltage was varied from zero to 350 volts, line to line, and the current and voltage were recorded. It was assumed that g_m, the conductance of the magnetizing branch, was zero.

d - For each voltage setting the impedance drop in the machine stator was subtracted from the terminal voltage on a per phase wye basis giving E_m.

e - Knowing E_m and I_m, b_m was calculated as I_m divided by E_m.

f - A plot of E_m as the ordinate and b_m as the abscissa gives the susceptance curve, Figure A-1, for this particular induction machine. The vertical portion of this curve indicates the minimum magnetizing susceptance.

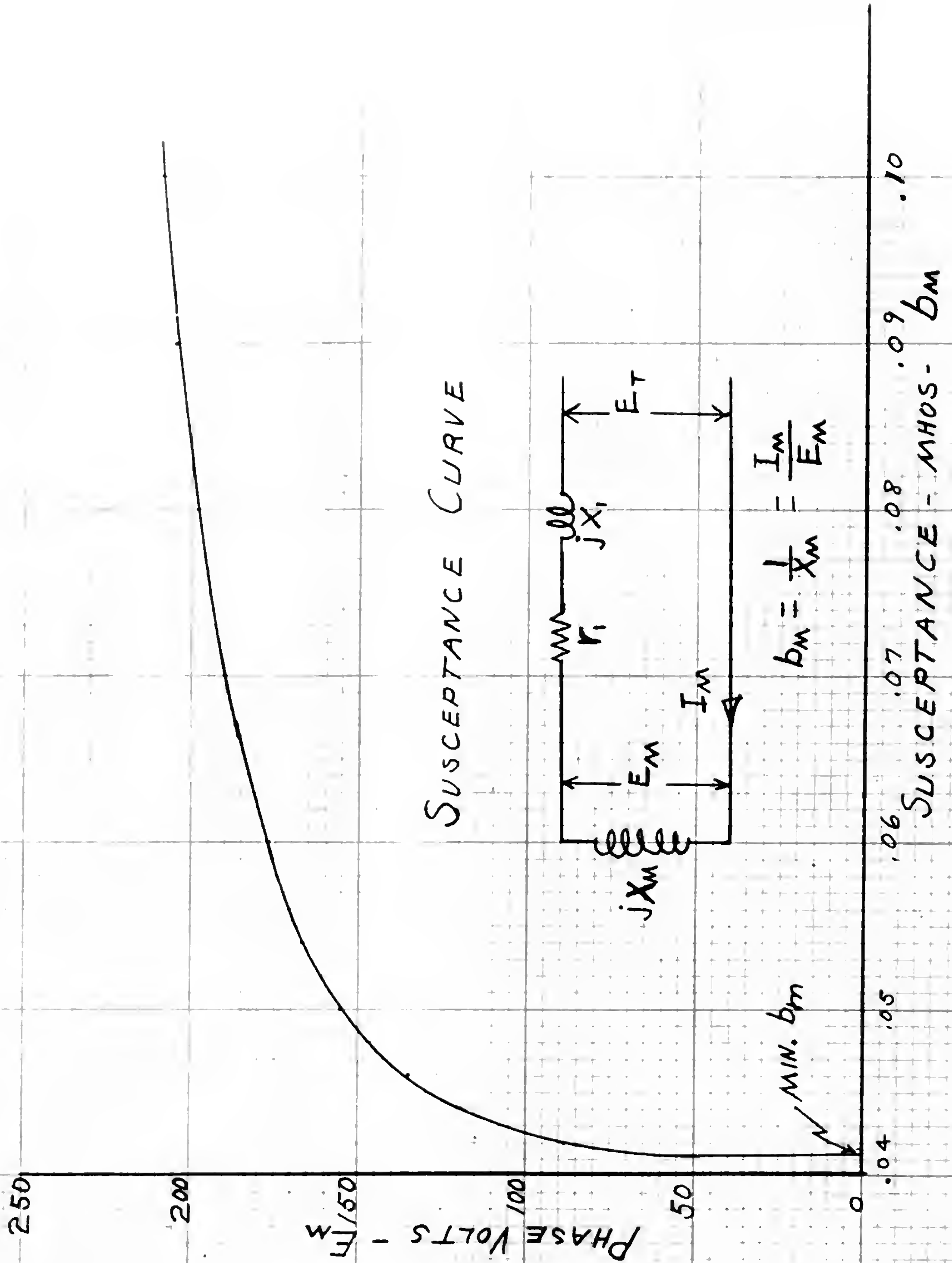

SUSCEPTANCE CURVE
jXM
EM
IM
r1
jX1
ET
bM = 1/XM = IM/EM
MIN. bm
PHASE VOLTS - EM
SUSCEPTANCE - MHOS - bM
0
50
100
150
200
250
.04
.05
.06
.07
.08
.09
.10

Figure A-1

APPENDIX 3

Brief Outline of Performance Calculation For Induction Generator as Set Up by Dr. James B. Friauf (5) of the Bureau of Ships.

The equivalent circuit for one phase of the induction generator, assumed to be wye connected, is shown in Figure A-2. Assumptions made are as follows:

a - That it is sufficient to consider only the fundamental frequency of current and voltage.

b - That r_1, r_2, X_1, and X_2 are constants independent of current and voltage.

c - That the resistances of the magnetizing reactance and the exciting capacitors are zero.

d - That the frequency is kept constant, the speed of the generator being regulated to satisfy this condition.

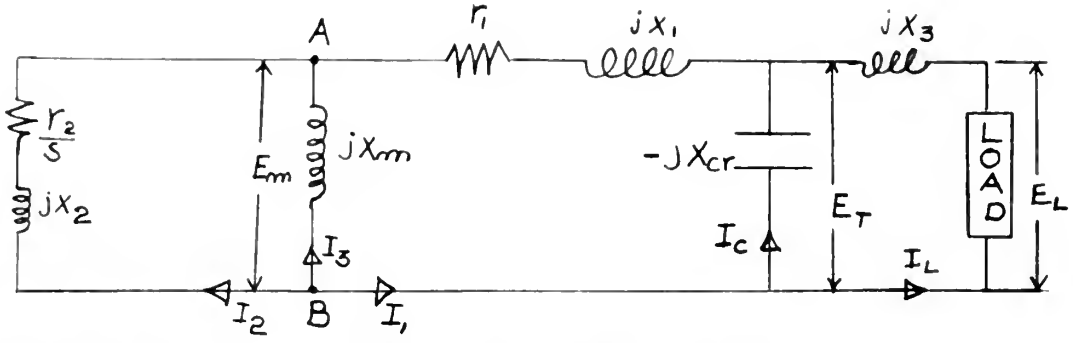
Refer to the equivalent circuit, Figure A-2. The physical concepts underlying this method of calculation are as follows:

$$\bar{I}_1 + \bar{I}_2 + \bar{I}_3 = 0 \qquad \text{a-1}$$

$$\bar{E}_m (\bar{Y}_1 + \bar{Y}_2 + \bar{Y}_3) = 0 \qquad \text{a-2}$$

$$\bar{Y}_1 + \bar{Y}_3 = -\bar{Y}_2 \qquad \text{a-3}$$

This method of calculation is based upon the fact that, in view of the above assumptions, each of the three admittances in Equation a-3 depends upon only one variable when the capacity for excitation and the



Equivalent Circuit For One Phase Of The Compound Connected, Capacitor Excited Induction Generator

Y_1 - Admittance of the complete circuit to the right of points A and B.

Y_2 - Admittance of the rotor circuit to the left of points A and B.

Y_3 - Admittance of the magnetizing reactance connected directly between points A and B.

Figure A-2

load power factor is kept constant. Under these conditions, again referring to Figure A-2, the voltage between A and B, E_m, is the only variable affecting Y_3. The slip, s, is the only variable affecting Y_2. The magnitude of the load impedance is the only variable affecting Y_1.

The admittance between points A and B is given by:

$$Y_3 = \frac{1}{jX_m} = -jb_m \qquad \text{a-4}$$

where b_m is the magnetizing susceptance given as a function of voltage in Figure A-1. On a vector admittance diagram such as Figure A-3 where the real component of admittance is plotted horizontally and the imaginary component plotted vertically, Y_3 will be represented by a vertical straight line directed downwards and having a length equal to b_m.

The admittance $-Y_2$ of the rotor circuit is:

$$Y_2 = \frac{1}{r_2/s + jX_2} \qquad \text{a-5}$$

Since r_2 and X_2 are constants, $-Y_2$ depends upon slip only. It can be shown that the $-Y_2$ locus is a circle defined as follows:

$$\text{abscissa of center} = 0 \qquad \text{a-6}$$

$$\text{ordinate of center} = \frac{1}{2X_2} \qquad \text{a-7}$$

$$\text{radius of circular locus} = \frac{1}{2X_2} \qquad \text{a-8}$$

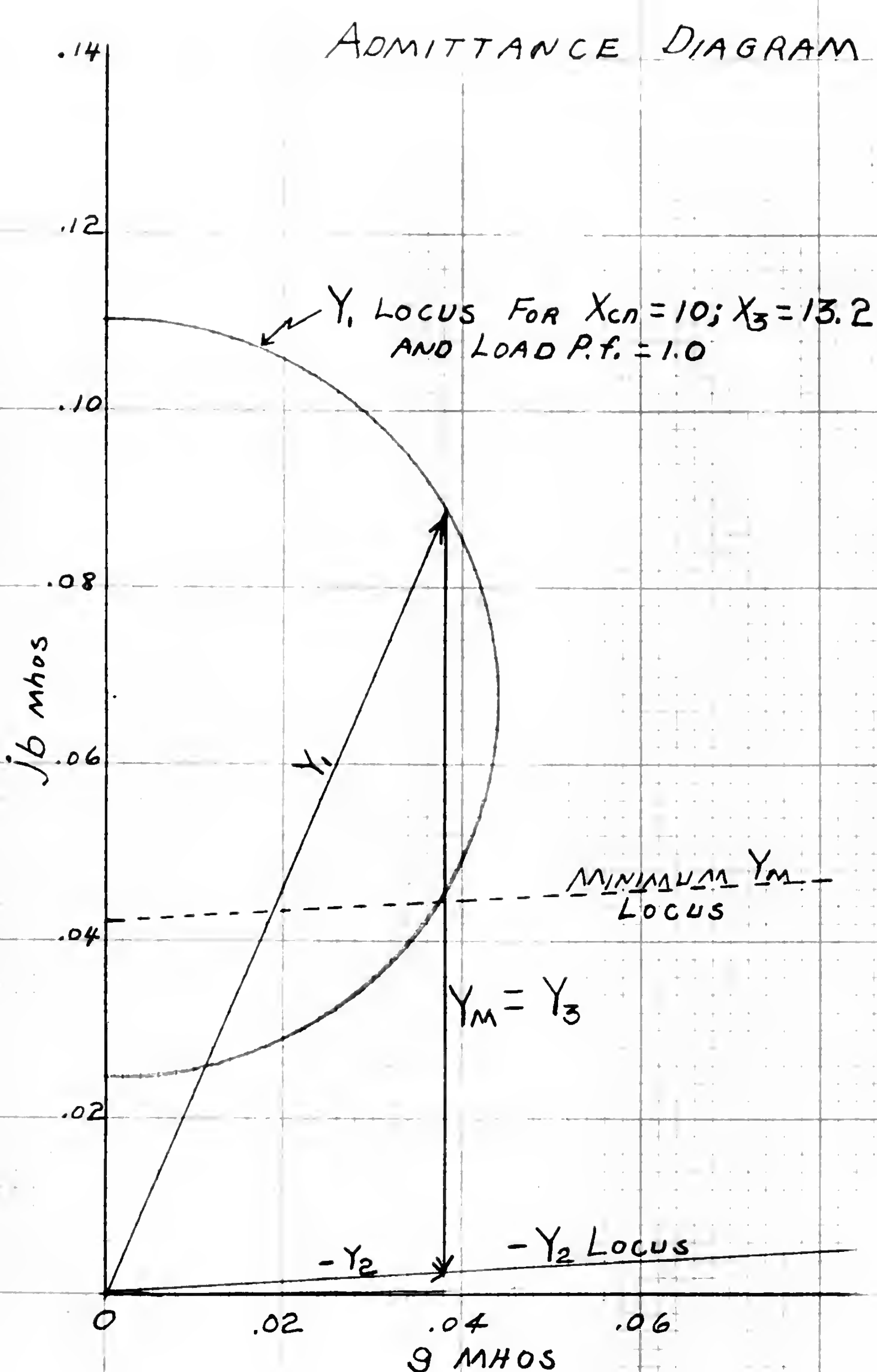

ADMITTANCE DIAGRAM
.14
.12
.10
.08
.06
.04
.02
jb mhos
Y1 LOCUS FOR Xcn = 10; X3 = 13.2
AND LOAD P.f. = 1.0
Y1
MINIMUM YM
LOCUS
YM = Y3
-Y2
-Y2 LOCUS
0
.02
.04
.06
g MHOS

Figure A-3

The admittance, Y_1, of the entire circuit to the right of the points A and B is as follows:

$$Y_1 = r_1 + jX_1 + \frac{1}{\frac{1}{-jX_{cr}} + \frac{1}{jX_3 + |Z|(\cos\phi + j\sin\phi)}} \qquad \text{a-9}$$

Since r_1, X_1, X_3, X_{cr}, and load power factor are constants, the only variable in Equation a-9 is the magnitude of the load impedance. This being the case it can be shown that the Y_1 locus is also a circle defined as follows:

$$\text{Radius} = \frac{\text{See equation I-4 and substitute } X_{cr} \text{ for } X_c}{} \qquad \text{a-10}$$

$$\text{Abscissa of center} = \frac{\text{See equation I-5}}{\text{Same denominator as a-10}} \qquad \text{a-11}$$

$$\text{Ordinate of center} = \frac{\text{See equation I-6}}{\text{Same denominator as a-10}} \qquad \text{a-12}$$

The step by step procedure is as follows:

a - The equivalent circuit and constants are shown in Figure A-2. For this particular series of calculations we let X_{cr} equal 10 ohms, X_3 equal 13.2 ohms, and load power factor equal unity. For these and all other calculations we neglect the resistance of the saturable reactor. We also neglect the resistance of the series inductance in the computation of the Y_1 locus in order to simplify calculations. However,

r_3 is considered in the solution for E_L after E_m has been determined.

b - The susceptance curve for the induction machine is shown in Figure A-1.

c - We wish to find E_L and I_L corresponding to various assumed values of slip.

d - Assume a value for slip, s.

e - Calculate $-Y_2$ for this particular value of s using Equation a-5. Plot computed $-Y_2$ on the vector admittance diagram as in Figure A-3 and enter computed value of $-Y_2$ on the tabular form, Figure A-4.

f - Calculate the coordinates of the center and the radius of the Y_1 circle using Equations a-10, a-11, and a-12. See Figure A-3.

g - Calculate the j component of Y_1 when the real component is equal to the real component of $-Y_2$. This may be done graphically on Figure A-3.

h - Subtract the j component of $-Y_2$ from the corresponding j component of Y_1 to get Y_m, the absolute value of which is b_m. Keep all this information in tabular form in Figure A-4.

i - Enter the susceptance curve on Figure A-1 with b_m and pick off the air gap voltage, E_m.

j - Knowing E_m and the circuit constants, by simple circuit analysis, calculate load current and voltage, I_L and E_L.

These values of E_L and I_L correspond to a particular exciting capacitance, a fixed series inductance, a certain assumed slip, and a specific load power factor. Repeat the above procedure for various values of assumed slip and a curve for any particular X_{cr} in Figure

4-3 may be plotted.

$Z_1 = .44 + j.81$ $Z_2 = .327 + j.584$ $Z_3 = 1.2 + j13.2$ LOAD P.F. = 1.0 $X_{cn} = 10$

$-S$	Y_2		Y_1		Y_m	E_m	I_1		E_T		I_{cn}		I_L		$I_L Z_3$		E_L	
SLIP	g_2	$j\,b_2$	g_1	$j\,b_1$	$j\,b_m$	E_m	real	j	–	j	–	j	–	j	–	j	–	j
.004	.0122	.00009	.0122	.1114	.1113	215	2.62	24.0	233.3	-12.7	1.27	23.3	1.35	0.70	-8.66	18.1	241.9	-30.5
.005	.0153	.00014	.0153	0.11	.1099	213	3.24	23.3	229.5	-12.9	1.29	22.9	1.95	0.35	-3.79	25.8	233.3	-38.7
.010	.0306	.00055	.0306	0.10	0.10	209	6.40	20.9	223.2	-14.4	1.44	22.3	4.96	-1.4	20.6	64.9	202.6	-79.3
.011	.0336	.00068	.0336	.098	.0973	208	6.98	20.4	221.4	-14.6	1.46	22.1	5.52	-1.7	24.7	72.3	196.7	-56.4
.012	.0367	.00079	.0367	.0943	.0935	206	7.56	19.4	218.4	-14.7	1.47	21.8	6.09	-2.4	34.4	79.5	178.0	-90.0
.013	.0398	.00092	.0398	.089	.0881	203	5.08	18.1	214.9	-14.5	1.45	21.5	6.63	-3.4	48.7	86.1	166.2	-100.6
.014	.0428	.00107	.0428	.082	.0809	198	8.48	16.2	207.4	-14.0	1.40	20.7	7.08	-4.5	62.5	91.6	144.9	105.6
.014′	.0428	.00107	.0428	.060	.0589	175	7.49	10.5	180.2	-10.7	1.10	18.0	6.40	-7.50	105.2	74.0	80.1	-90.7
.0145	.0444	.00115	.0444	.0745	.0733	192	5.51	14.3	199.8	-13.2	1.32	20.0	7.19	-6.65	75.02	72.4	117.1	[illegible]

SAMPLE CALCULATIONS

APPENDIX 4

Name Plate Data

Generator:

5 KVA

220 Volts

13 Amperes

0.9 Power Factor

3 Phase

60 Cycle

1200 RPM

Serial No. 4844608

Saturable Core Reactor:

5 KVA

240 Volts

3 Phase

60 Cycle

I_{dc} Maximum - 0.5 Amperes

Serial No. XJ

DC Drive Motor:

5 Horsepower

115 Volt

38 Amperes

Shunt Field

850/1700 RPM

Serial No. 51335

Synchronous Motor:

5 KVA

220 Volt

1200 RPM

13 Amperes

3 Phase

60 Cycle

0.9 Power Factor

Serial No. 8S3N9961

Wave Analyser:

General Radio Type 736-A

Serial No. 1492

Industrial Analyser:

Weston Model 639, Type 2

Serial No. 3685

Industrial Analyser:

Westinghouse Type TA

Serial No. 2479598

Strobotac:

General Radio Co. Type 631B

Serial No. 11782

Cathode-Ray Oscillograph:

Dumont Type 304H

Serial No. 7849

Tachometer:

Jagabi Chronometer Type, Serial No. 313082

APPENDIX 5

Experimental Data

See pages 51 and 52.

← LOAD Syn. Motor 1200 rpm				GENERATOR $Z_3 = 0.6 + j6.6$									D.C. DRIVE MOTOR			
I_L	E_L line	K.W.	P.f. lag	I_{dc}	E_T line	I_1	K.W.	P.f. load	I_r	i_r	I_{cr}	Eff.%	E	I	I_f	RPM
1.8	200	0.58	1	365	198	6.0	1.0	0.48	13.3	8.8	5.2	45.7	115	14	0.80	[illegible]
3.2	200	1.08	1	350	206	7.1	1.5	0.59	12.8	8.7	6.4	58.9	115.5	17.5	[illegible]	1214
5.0	200	1.72	1	325	210	8.6	2.1	0.68	12.0	7.9	7.6	66.8	115	27.5	0.80	[illegible]
6.4	200	2.10	1	308	220	9.6	2.7	0.72	11.3	7.6	9.1	66.3	115	33.3	[illegible]	[illegible]
7.8	200	2.65	1	283	228	11.1	3.3	0.75	10.8	7.2	10.5	68.5	115	39.5	0.80	[illegible]
9.2	200	3.15	1	260	236	12.0	3.8	0.76	8.8	6.6	12.2	70.1	114	46.0	0.80	[illegible]
10.3	200	3.55	1	240	244	13.0	4.1	0.75	9.0	6.1	13.7	71.8	114	52.0	0.80	[illegible]
11.4	200	3.90	1	220	254	13.7	4.7	0.76	8.5	5.8	15.1	70.0	114	58.0	0.80	[illegible]
1.2	200	0.34	0.8	365	207	5.8	0.8	0.38	13.3	8.9	6.0	33.2	116.5	12.0	0.80	1209
3.0	200	0.94	0.8	342	220	7.1	1.4	0.52	12.8	8.6	7.7	54.2	117.0	18.5	0.80	1213
4.5	200	1.44	0.8	322	230	8.1	2.0	0.59	12.4	8.2	9.2	60.9	116.5	24.0	0.80	1214
6.6	200	1.85	0.8	290	260	9.6	2.5	0.56	11.2	7.7	13.0	62.8	116.0	30.0	0.80	[illegible]
8.5	200	2.40	0.8	262	278	11.1	3.1	0.57	10.4	7.2	15.4	66.4	115.5	36.5	0.80	[illegible]
10.0	200	2.85	0.8	222	294	12.4	3.65	0.57	9.4	6.6	18.2	66.4	115	44.0	0.80	[illegible]
1.8	200	0.38	0.6	355	218	6.0	0.70	0.35	13.1	[illegible]	7.0	38.6	116.5	[illegible]	[illegible]	[illegible]
[illegible]	200	0.56	0.6	330	239	7.5	1.30	0.44	12.5	8.5	9.8	52.3	116.0	[illegible]	0.80	[illegible]
5.5	200	1.10	0.6	308	255	8.2	1.70	0.45	11.5	8.3	11.9	53.5	116	21.5	[illegible]	[illegible]
6.6	200	1.40	0.6	290	270	9.1	2.10	0.46	11.6	8.0	13.6	56.5	116.0	[illegible]	[illegible]	[illegible]
8.4	200	1.75	0.6	255	[illegible]	10.6	2.50	0.45	10.4	7.5	16.8	59.4	116.0	[illegible]	[illegible]	[illegible]

$\therefore Z_3 = 1.2 + j\,13.2$

SYN. MOTOR LOAD RPM = 1200				GENERATOR									D.C. DRIVE MOTOR			
I_L	E_L line	K.W.	P.f.L	I_{DC}	E_T line	I_1	K.W.	LEAD P.f.g	I_n line	I_n ø	I_{cr}	Effi. OVERALL	E	L	I_f	RPM
2	200	.70	1	368	210	6.5	1.1	.49	13.5	9.0	6.2	50.5	115.5	16	0.80	1209
3	200	1.02	1	352	215	7.2	1.5	.47	13.2	8.8	6.8	55.7	115	19.5	0.80	1213
4	200	1.40	1	345	225	8.1	1.9	.59	13.1	8.7	8.1	61.8	115	23.2	0.80	1214
5	200	1.65	1	335	235	8.9	2.3	.63	12.8	8.5	9.2	64.8	115.5	27.2	0.80	1217
6	200	2.00	1	325	250	10.0	2.7	.64	12.5	8.45	10.8	65.1	115.5	32	0.80	1219
7.9	200	2.74	1	301	280	11.8	3.5	.63	12.3	8.4	14.1	65.4	115.0	42	0.80	1221
			LAG													
2.40	200	.68	0.8	371	242	7.5	1.2	.40	14.2	9.6	8.6	43.7	115.5	17.5	0.80	1207
3.65	200	1.02	0.8	360	260	8.5	1.7	.46	14.1	9.8	10.2	49.1	115.5	22	0.80	1209
4.91	200	1.36	0.8	352	285	10.1	2.2	.43	14.2	9.9	13.0	52.2	115.5	26.7	0.80	1211
5.7	200	1.50	0.8	340	302	11.2	2.4	.40	14.1	10.0	15.0	52.6	121	28	0.80	1212
1.55	200	0.34	0.6	378	230	6.5	0.85	.35	14.3	9.5	7.5	29.3	122	13.0	0.80	1206
3.05	200	0.68	0.6	370	265	8.3	1.30	.36	14.5	10.1	10.4	40.8	122	17.5	0.80	1208
4.0	200	0.86	0.6	365	282	9.1	1.55	.37	14.2	10.1	11.8	44.3	122	20.0	0.80	1201
4.6	200	0.98	0.6	359	292	10.0	1.80	.36	14.6	10.3	13.0	44.7	122	22.0	0.80	[illegible]
0	SH															
13.0	SHORT CIRCUIT	—	0 lag	122	300	9.7	1.0	0 lead	6.2	4.7	22	→ 0	122	17.0	0.80	1204
No load	200	0	–	370	200	5.4	0.4	–	13.6	9.0	5.1	0	122	8.2	0.80	1204

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